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VISUALIZATION TECHNIQUES FOR THE ANALYSIS OF NETWORK SIMULATION RESULTS

by

Christopher Main

A Thesis

Presented to the Faculty of

Bucknell University

in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science with Honors in Computer Science

May 8, 2013

Approved:

Luiz Felipe Perrone
Thesis Advisor

Stephen Guattery
Chair, Department of Computer Science

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Contents

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Abstract

The Simulation Automation Framework for Experiments (SAFE) streamlines the design and execution of experiments with the ns-3 network simulator. SAFE ensures that best practices are followed throughout the workflow a network simulation study, guaranteeing that results are both credible and reproducible by third parties. Data analysis is a crucial part of this workflow, where mistakes are often made. Even when appearing in highly regarded venues, scientific graphics in numerous network simulation publications fail to include graphic titles, units, legends, and confidence intervals. After studying the literature in network simulation methodology and information graphics visualization, I developed a visualization component for SAFE to help users avoid these errors in their scientific workflow. The functionality of this new component includes support for interactive visualization through a web-based interface and for the generation of high-quality, static plots that can be included in publications. The overarching goal of my contribution is to help users create graphics that follow best practices in visualization and thereby succeed in conveying the right information about simulation results.

Chapter 1

Introduction

The use of graphics to explore interesting characteristics of data has greatly increased in popularity over the past fifty years. To a great extent, this increased attention is due to the work of the pioneers of exploratory data analysis, most notably John Tukey [46] and William Cleveland [15]. Both of these statisticians showed that graphics were a very effective tool in analyzing large datasets. The other major contributing factor to the increase in use of information graphics was the widespread adoption of the personal computer. With computers accelerating the amount of data being produced, collected, and stored, data visualization became a necessity in gleaning knowledge from a sea of numbers. This fact is especially true for scientific data sets which are often large and difficult to interpret.

Network simulation is one area of scientific research that creates massive amounts of data [41]. Simulation has become a popular tool in network research because physical networks are often expensive to build and difficult to test with precision. Simulation allows researchers to conduct experiments with high-quality models of real world entities and observe how various changes to a network affect its operating characteristics. Simulation has the added benefits of making certain metrics easier to observe and giving the experimenter precise control over the experimental scenario.

In many cases, the complexity of the simulation model leads to numerous potentially interesting streams of data which, depending on the length of the simulation and the sampling interval, can produce millions of data points.

Unfortunately, numerous credibility problems exist in current network simulation methodology and output analysis practices. Researchers often publish simulation results that lack repeatability and are statistically biased. Furthermore, many publications in network simulation that use graphics fail to include titles, labels, and legends. These publications have made their way to some of the most prestigious conference venues, including the ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc) [31].

Frameworks such as Akaroa2 [30], STARS [35], and SimProcTC [17] have contributed to automating experiment execution and output data analysis. However, they don't provide all the guidance that could help less experienced users of network simulation. Perrone et al. [38] argue that network simulation is a powerful educational tool for both graduate and undergraduate students, yet much of a student's time is spent learning the inner-workings of a particular simulator. A tool that makes credible simulation experiments accessible at the undergraduate level would be invaluable in both networking and simulation courses. Such a tool would also allow researchers in the field of network simulation to publish statistically credible and repeatable results.

A crucial part of reporting experimental results is making them understandable and meaningful. Years of research have shown that presenting information visually greatly improves the decipherability of results [46]. There is a serious need in the network research community for a tool that allows users to generate such graphics in an intuitive manner.

One major trend in technology over the past twenty years has been a movement to shift services to the cloud, that is, to remote machines accessed over the Internet. Many of today's most popular applications are web-based, with the majority of the programming logic and data living in the cloud. There are many advantages in the

use of web-based applications, one of the most imporant being their accessibility and portability. The user only needs a web-browser and an Internet connection to use the application.

It is no surprise that using the web as a platform for data visualization is an idea that is quickly gaining popularity. The web has always been a platform that promotes interactivity and exploration, both of which are useful components for constructing high-quality data visualizations. There exist several web-applications that build high-quality, interactive visualizations from user uploaded data [9; 8].

The goal of my research was to survey various modern visualization techniques and to evaluate their suitability in the study of network simulation datasets. To this end, I have constructed a tool that allows researchers to explore interesting characteristics of their simulation data and produce statistically valid, publication-quality graphics.

The remainder of this thesis is structured as follows. Chapter 2 describes various credibility issues in network simulation and how these issues can be addressed with a framework for automating the simulation workflow. Part of such a framework is a tool for visualizing network simulation results in a meaningful manner. Chapter 3 provides background information regarding data visualization. Much research has been conducted over the past 60 years in data analysis and visualization, and this can be applied to a component for visualizing network simulation data. Chapter 4 details many of the design considerations that went into the making of this component. These design considerations were influenced by both the goals of SAFE and best practices from the literature in information graphics. Chapter 5 examines the most common scenarios for the use of SAFE's visualization component in the form of case studies. These case studies illustrate that SAFE's visualization component helps to avoid many of the pitfalls common in network simulation research. Chapter 6 puts SAFE and its visualization component into context, comparing it to other tools of similar scope. Finally, Chapter 7 draws conclusions from my work and discusses plans for future work.

Chapter 2

Motivation

While research in network simulation has produced interesting results for many years, it is not a field without issues. The complexity of network simulators makes them suitable only for experienced researchers. Studies have also shown that even experienced researchers can make mistakes that find their way into publications at well-known venues [31]. As argued in the literature, one possible way to avert this problem is with the use of software tools that lead to less mistakes and more credible results [38]. These tools have the added benefit of bringing the power of cutting-edge network simulators to inexperienced users such as undergraduate students. Since output analysis is a critical step in network simulation studies, such an automation tool must have a component for visualizing and analyzing experimental results. The focus of my work was to create such a component, adhering to the best practices of network simulation research and data visualization.

2.1 Issues in Network Simulation

Numerous papers have been published concerning credibility problems in network simulation methodology. Early work by Pawlikowski et al. [37] claimed that this cri-

sis of credibility could be resolved with the application of common-sense guidelines, namely the use of high quality random number generators and rigorous output data analysis. Unfortunately, the roots of the problem went deeper, with Kurkowski et al. [31] showing that many published studies leave something to be desired in reproducibility, statistical rigor, and the suitability of experimental scenarios. They describe in detail how publications have failed to deal properly with important issues in the simulation experimental workflow, exposing a number of pitfalls that have traditionally tripped up network simulation researchers.

Kurkowski et al. [31] and Pawlikowski et al. [37], have analyzed and found credibility issues in a large body of publications from highly regarded sources including the proceedings of the IEEE International Conference on Computer Communications (INFOCOM), the ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc), and journals such as the IEEE Transactions on Communications, IEEE/ACM Transactions on Networking, and Performance Evaluation Journal. It is fair to assume that the problems that undermine the credibility of network simulation studies extend well-beyond these venues and are at least as severe.

Of specific interest to my work are findings made by Kurkowski et al. [31] relating to the use of plots to report network simulation results. Of the 114 surveyed publications, 112 of them of them included some type of plot. Of these 112 publications, only 100 had legends on the plots, only 84 had units or labels associated with the data, and only 14 of them used confidence intervals. Although such mistakes are easy to avoid, they can lead readers to misinterpret the data and make wrong conclusions about experiments.

2.2 The SAFE Project

The Simulation Automation Framework for Experiments (SAFE) [39] was conceived to address many of the issues of credibility in network simulation research by supporting users in following best practices. The philosophy behind SAFE's functionality is

to apply automation to the simulation workflow, so that the experimental method is followed rigourously *by default*. This allows users to focus on the science rather than on the details of the workflow methodology. It also stores data concerning an experiment's configuration and execution so that an experiment can later be reproduced and verified. SAFE is built to support the open source and widely used ns-3 network simulator. The ns-3 community has a need for a tool like SAFE and the intent is that the ns-3 community will help to further develop SAFE in the future.

Bryan Ward [50] and Andrew Hallagan [27] carried out much of the early development work for SAFE, while working toward their honors theses research. Throughout the spring and summer of 2012, I completed and expanded upon what Ward and Hallagan had started. I integrated many of the core components of SAFE into a coherent piece of software that covered the majority of the experimental workflow. The results of this effort appeared in a paper presented at the 2012 Winter Simulation Conference [39] and are summarized in the remainder of this section.

This thesis focuses on my effort to bring high quality methods of visualization design and output analysis to augment SAFE's functionalities.

2.2.1 Educational Value

One of the driving forces behind the creation of SAFE was its potential educational value. Without a framework such as SAFE, a student can spend considerable time learning enough about a network simulator in order to conduct even a simple experiment [38]. On top of the steep learning curve of the network simulator, students cannot be expected to avoid many of common mistakes made by experienced researchers in network simulation, as described in Section 2.1.

SAFE automates much of the workflow of network simulation, allowing even inexperienced undergraduate students to make use of ns-3 in their classes and research. An example of a scenario where this would be very valuable is in an undergradu-

ate networking class. In this scenario the professor will craft ns-3 simulation scripts and pass them to students, who define parameter values and run experiments via an interface offered via a web-browser. The same interface gives students access to a web-based data visualization tool, from which they can analyze the experimental results and generate graphics to include in homework and reports. The advantage to this approach is that all of this can be done with little to no knowledge of ns-3: students don't have to spend time learning the simulator and can go straight into creating and evaluating experiments with various networking scenarios.

2.2.2 User Stories

SAFE supports two types of users, defined as follows. A *power user* is defined as an individual who is comfortable with the inner-workings of ns-3 and experienced with common UNIX system applications such as `ssh` and `sftp` [10], which enable remote access and file transfer. A *novice user*, on the other hand, may have little to no knowledge of ns-3, and will access the system via an easy to navigate web user interface. While a graduate student would likely fall into the power user category, an undergraduate would likely fall into the novice user category. SAFE is designed to serve the two types of users with different interfaces supported by a common backend.

Support for Power Users

Figure 2.1 shows an overview of the the architecture of SAFE and the workflow for a power user. The workflow of SAFE begins at (1), when a user writes their own simulation script and places it into the ns-3 directory on their own machine. In (2) the user crafts a file describing the experiment they wish to run using the Experiment Description Language (NEDL) [27], an XML-based language designed to describe experiments to be conducted using SAFE. The user must also craft a small configuration file which points to both their simulation script and their experiment description file.

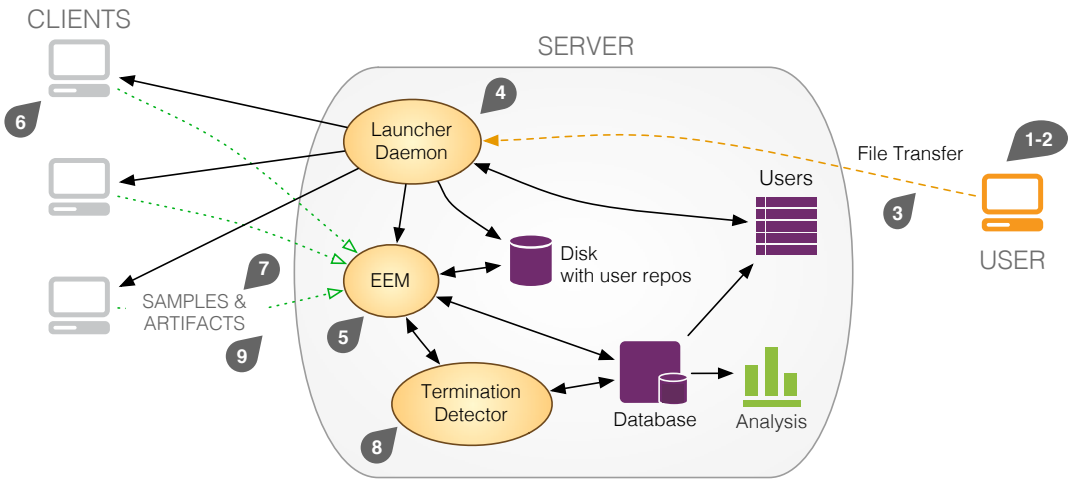


Figure 2.1: High level view of power user workflow and system architecture.

After the configuration file has been written, the user proceeds to (3) in which they use `sftp` to connect to the server. The server contains a database of user credentials for those who are authorized to access the system. Each user has their own directory on the server for which they are granted access upon a successful login attempt. After the user has successfully logged in, they upload to the server their experiment bundle, which includes their ns-3 installation, simulation script, experiment description file, and configuration file. As soon as this is completed, the user logs out of the server and their experiment execution begins.

When the server realizes that it has a new experiment to run in (4), the launcher daemon begins sending the compressed experiment bundle to the client machines, in parallel connections. As this is happening, the launcher daemon also starts the Experiment Execution Manager (EEM) in (5). The EEM will take the user's experiment description file and generate the *experiment space*. The experiment design space comprises *design points*, each of which corresponds to one simulation run to be executed on one of the client machines. As soon as a client machine receives the experiment bundle, it uncompresses it and starts *simulation client* processes. In case this client machine has multiple cores, one simulation client process is started for each of its cores. The simulation client processes register with the EEM and then wait to

receive design points for execution (6).

As soon as the simulation client receives a design point, it starts ns-3 and begins executing the simulation. At some point, the ns-3 run starts to generate output data in the form of 'samples,' which are passed to the local simulation client for relaying to the EEM (7). The EEM receives samples and stores them in a database along with all the data pertaining to the experiment. Meanwhile, a *termination detector*, running in the server, monitors incoming samples to determine when enough data has been collected to reach an appropriate level of precision for statistical interval estimation. When this condition is reached, the experiment can be terminated (8) and the EEM tells all clients to stop their ns-3 runs. As the clients stop, they clean up any temporary files or processes that were created during the execution of the experiment.

Clients finalize their operation by sending to the EEM any experiment artifacts (files) that may have been generated. Upon receiving artifacts, the EEM stores them to disk, in the respective compartment for the user (9). After all artifacts have been collected, the experiment is marked as completed and the analysis of results can begin.

Currently, power users must use the web interface in order to query the database and analyze experimental data. Future plans include adding support for static plot generation that could be scripted by the user. This feature could be based of of the web-based static plotting functionality, with output files being put into the user's compartment instead of being displayed in the web user interface.

Support for Novice Users

Figure 2.2 shows an overview of the the architecture of SAFE and the workflow for a novice user. Although the underlying insfrastructure of SAFE is very similar for both novice and power users, the user interfaces are quite different. Novice users interact with SAFE solely via a web-based interface offered through a standard web browser.

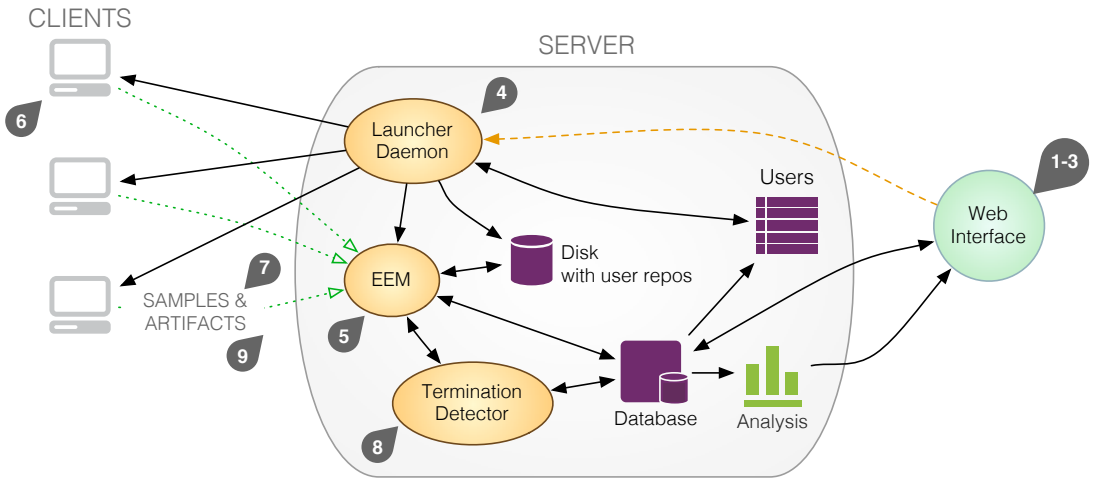


Figure 2.2: High level view of novice user workflow and system architecture.

When a novice user wishes to use SAFE, they first point their web browser to the address (URL) of the SAFE server. The user is first presented with a login prompt, where they enter their user credentials to be verified against SAFE's user database (1). After successfully logging in, the user will have access to a variety of ns-3 simulation scripts that have been made public by power users, or they can upload their own simulation script if they choose (2). After selecting a simulation script, the user is presented with a form that allows them to configure their experiment (3). After this step is complete, SAFE will have generated a NEDL file and know the location of the simulation script to be executed. From this point on, SAFE proceeds with the same steps (4)-(9) described in Section 2.2.2.

As stated previously, the main focus of the research work presented in this thesis was to build a tool for data visualization. This tool is an integral part of SAFE, which is presented to the user following step (9) in the workflow. The user is notified through the web interface when their experiment is complete and they can proceed to the data analysis step which is described in detail in Chapter 4.

2.3 Chapter Summary

SAFE was conceived to address the crisis of credibility in network simulation research. By automating much of the experimental workflow, SAFE helps both experts and novices in network simulation research to avoid mistakes that lead to unreliable results. In addition to automating much of the experimental workflow, SAFE stores experiment configuration and execution data to make the experiment reproducible by others. This chapter introduced the reader to the broader architecture of SAFE and identfied the main focus of this thesis, which is the research and the development of a new framework component that allows users to visualize and analyze experimental results, as well as to produce publication-quality graphics from them.

Chapter 3

Background

Using graphics to illustrate interesting characteristics of large data sets is not a new idea. Research is this field spans a variety of disciplines including, but not limited to, graphic design, statistics, cognitive psychology, and computer science. In order to design and construct the visualization component for SAFE, I researched the best practices from all of these disciplines. This chapter summarizes the findings from the literature that directed my implementation.

3.1 Semiology of Graphics

One of the most important and influential works ever published in the field of information graphics is Jacques Bertin's *Semiology of Graphics* [12]. Originally published in French in 1967, Bertin's work paved the way for the fields of exploratory data analysis and information visualization. A cartographer by trade, Bertin developed an insightful theory of graphics almost entirely through his own perception. Bertin's early work has inspired much research in the field of information graphics and his work has held up in modern studies of cognition and perception [23].

3.1.1 Purpose of Graphic Representation

According to Bertin [12], graphic representation serves three purposes:

1. Record Information,
2. Communicate Information, and
3. Process Information.

The main motivation for my work was to enable the best cognitive processing of scientific data presented visually. Bertin [12] describes this purpose in more detail as "reducing the comprehensive, nonmemorizeable inventory to a simplified, memorizable message." Ultimately, whether users are experienced researchers or students, they want to be able to draw some meaningful message from the data resulting from their experiments. Information graphics are among the best methods to identify such messages in large data sets.

3.1.2 Information

Bertin [12] defines information as "a series of correspondences observed within a finite set of variational concepts of 'components.' All the correspondences must relate to a variable common ground, which we will term the 'invariant.' " This definition is best understood with an example. Figure 3.1 shows a graphic that could be constructed from network simulation data. In this graphic the components are time (in seconds) and size (in queue items). The invariant is the size of a queue, expressed in the total number of items therein. Another data series could be added to Figure 3.1 as long as its addition follows the invariant.

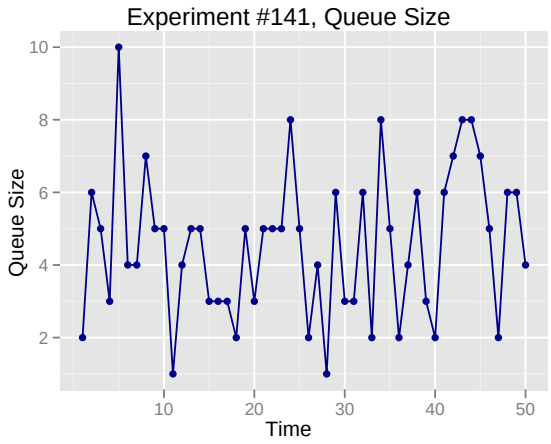


Figure 3.1: Typical plot produced by network simulations (synthetic data).

3.1.3 Retinal Variables

There exist six retinal variables according to Bertin [12]: Size, Value, Texture, Color, Orientation, and Shape. These variables represent variations in perception that occur above the plane of the graphic and are often discussed in the context of experimental psychology as defining how humans perceive depth. In creating two-dimensional graphics, these variables represent all of the tools in the hands of the designer.

Size describes a variation in the dimensions of a mark on a plot which causes perceptual stimulus. This variable applies to points, lines, and areas. An important consideration about size variation is that it is *dissociative*, meaning that it will dominate any other retinal variable with which it is combined.

Value variation describes the ratio between black and white objects on a given surface. An order exists within value variation, from light to dark, and not following this ordering will produce a graphic that is not suitable for visual interpretation. Interestingly, value is also dissociative and not quantitative by itself. When combined with size variation though, value variation can be used to represent quantitative data.

Texture describes the number of distinct marks or symbols within a certain area. Examples of common texture elements include arrays of circles, squares, or lines. The creator of a graphic needs to take care when using textures as they can cause uncomfortable visual sensations. This effect is commonly referred to as *moiré vibration* [45], and is demonstrated in Figure 3.2.

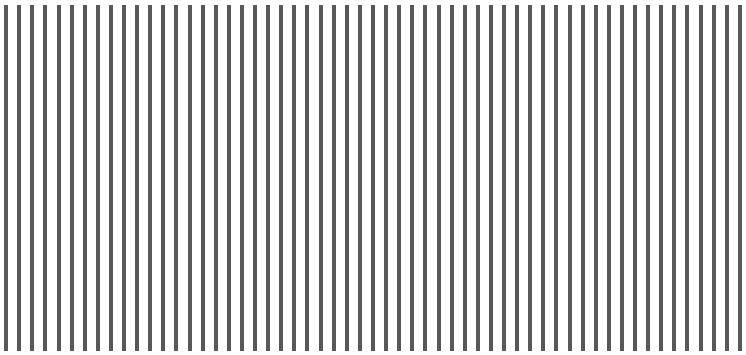


Figure 3.2: A graphic which exhibits moiré vibration.

Color variation refers to changes that can be perceived between identical areas which have the same value. There are many aspects of utilizing color variation which can trip up a designer, such as accidentally creating an association between color variation and order where one does not exist in the data. Due to these concerns and since color is used in SAFE's visualization component, it is discussed in more detail in Section 3.1.4.

Orientation is "the difference in angle between fields created by several parallel signs" [12]. For orientation variation to create visual stimulus, the shapes must be linear. Furthermore the designer of the graphic cannot exploit too many variations on orientation. There must be easily recognizable categories of variation for them to have visual meaning.

Shape, the final retinal variable, describes the variation in appearance of objects of equal sized area. Obvious examples of shapes are circles, squares, and triangles, but

countless others exist. In certain types of graphics, such as maps, the use of mimetic shapes, or shapes that imitate what they represent, can make a graphic much easier to comprehend. It is important, though, not to use mimetic shapes where the mark is not intended to have any particular meaning.

3.1.4 Notes on Color Variation

To understand how color variation can be used in the construction of graphics, one must first understand the concepts of *color hue* and *color value*. Color hue can be divided into the following categories: violet, blue, green, yellow, orange, red, purple, and gray. Color value is the percentage of black in the corresponding gray. A pure tone, or saturated tone, is one that involves no mixture with other colors. Such a tone is neither darkened by the addition of black, or lightened by the addition of white. Examples of saturated tones are pictured in Figure 3.3. Constant value tones, on the other hand, have some addition of black or white to produce the tone. Examples of saturated tones are pictured in Figure 3.4. What is important to take away from this discussion is that saturated tones are not of constant value; rather, they vary in value according to the color.

The difference between saturated tones and constant value tones leads to two distinct uses of color in information graphics. If the designer wishes colors to represent ordered values, then saturated tones should be used. The ordering of such tones is also important, with yellow denoting the smallest value and either purple or violet representing the largest value. The values in between yellow and purple should be orange and red, in that order. This ordering is referred to as the "warm" tones. The colors between yellow and violet should be green and blue, in that order. This ordering is referred to as the "cool" tones. One should not mix warm and cool tones when denoting order, as it creates visual confusion. If one does not want color to be associated with ordered values, then constant value tones should be used.

When using constant value tones it is important to maintain a level of selectivity,

Figure 3.3: A collection of saturated, or pure, tones.

Figure 3.4: A collection of constant value tones which have been darkened from saturation.

or "distinguishability," between colors. Selectivity is maximal near saturated tones and diminishes as the tone moves towards either white or black. However, there are tones that are more selective than others depending on the tone's value. For example, with light value tones, blue, purple, violet, and red tend to look grayish and should not be used. It is advisable to choose steps around yellow, from green to orange.

While color variation is an excellent technique for differentiation, it does have some notable disadvantages. Individuals with anomalies in chromatic perception, such as color blindness, may perceive little to no information in a graphic constructed with color. Reproducing color on paper can also be difficult, and color graphics when reproduced monochromatically may have little value. To mitigate these disadvantages, it is good practice to combine color with another variable such as texture or size.

3.1.5 Time Series

While numerous types of information graphics exist, such as maps and networks, time series diagrams are of central interest in relation to my work. Bertin [12] describes a number of issues that may affect the perceptibility of a time series graphic. He

claims that optimal angular perceptibility occurs around 70 degrees, so the scale of the domain should be adjusted to not have overly pointed or flat curves. He also describes using points affixed to a line to obtain precision readings, a technique used in SAFE's visualization component.

3.2 Exploratory Data Analysis

Some of the most influential work concerning data visualization in the field of statistics comes from John Tukey [46] and William Cleveland [15; 16]. Tukey [46] legitimized exploratory data analysis (EDA) as a technique to gain a better understanding of data. Cleveland built upon Tukey's work providing guidance on how the techniques associated with EDA could be used most effectively. Since a variety of these techniques are useful in analyzing data produced by network simulation, SAFE's visualization component was designed to incorporate them.

3.2.1 Data Summaries

One of the simplest and most effective ways to gain a better understanding of a large data set is a *data summary*, which is defined as either numerical or graphical information that reveals big picture characteristics of the data. It is important to understand that data summaries are not the details; they do not revel the unusual characteristics of the data.

The most common graphical method for showing summary statistics is the *box-and-whisker plot* as shown in Figure 3.5. This is a graphical method for displaying five-number summaries which include the sample minimum, the first quartile, the median, the third quartile, and the sample maximum. The height of the box part of a box-and-whisker plot goes from the first quartile to the third quartile with the median drawn as a line. The whiskers can either extend to the sample minimum

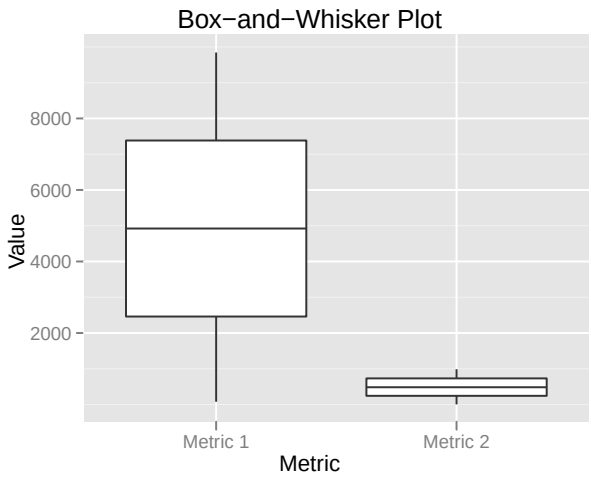


Figure 3.5: Example of a Box-and-whisker Plot.

and sample maximum, or a variety of other values, such as one standard deviation of the data. Tufte [45] proposes an alternative representation of Tukey's [46] box-and-whisker plot that uses even less ink by compressing the box horizontally along the x-axis into a line.

3.2.2 Data Distributions

There are numerous graphical methods for analyzing and comparing the distributions of data. One of the simplest methods is to use box-and-whisker plots, as discussed in Section 3.2.1. Another common method is the *quantile-quantile plot* (Q-Q plot). This type of graphic shows two distributions against each other; if they are similar the points of the plot will fall along the line $y = x$. An example of a Q-Q plot is shown in Figure 3.6, with the distribution of automobile miles per gallon being compared to a normal distribution. Comparing data to theoretical distributions in this manner helps to determine if data fits a certain theoretical model [46; 15].

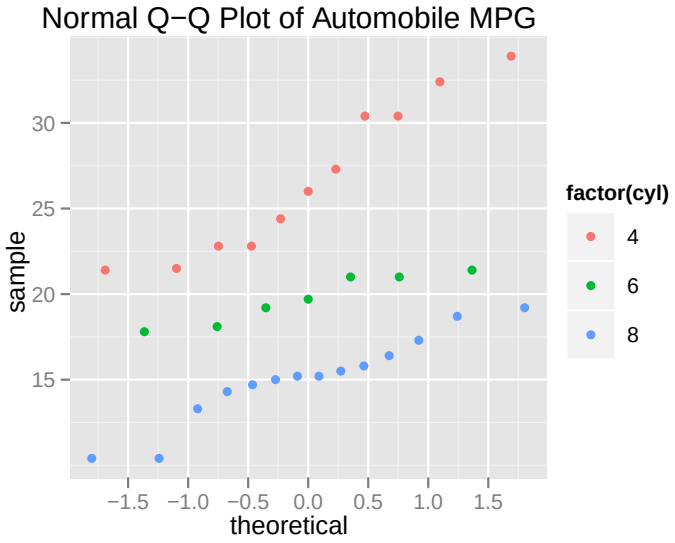


Figure 3.6: Example of a Normal Q-Q Plot, plotting the miles per gallon ratings of automobiles with 4, 6, and 8 cylinders against the normal distribution.

3.3 Information Visualization Evolves

Taking obvious inspiration from Jaques Bertin, Edward Tufte published two of the most widely read books on information graphics: *The Visual Display of Quantitative Information* [45] and *Envisioning Information* [44]. These two works expanded upon Bertin's [12] ideas and made them appealing to a wider audience. Much of the inspiration for SAFE's visualization component was derived from these seminal works.

3.3.1 Micro/Macro Visualizations

A *micro/macro visualization* provides an overall picture of the data while also providing a deeper level of detail upon closer inspection. A perfect illustration of micro/macro design is the Vietnam Veterans Memorial in Washington, D.C., pictured

Figure 3.7: The Vietnam Veterans Memorial, a perfect example of micro/macro design (source: National Archives at College Park, public domain).

in Figure 3.7 [44]. From a distance, the message conveyed to the observer is the magnitude of the loss of human lives: the aggregate image of 58,195 names carved into stone. Getting closer, the observer sees information on individual fallen soldiers, such as names and other details.

The general idea of the micro/macro design is to expose larger trends and add detail on demand. In such a visualization, control is given to the viewer, not to the creator of the visualization. The viewer chooses which aspects of the information merit further inspection. Also, micro/macro visualizations do not make viewers rely on visual memory to make comparisons or choices. This gives the viewer a better chance of comprehending the data and finding interesting relationships [44].

3.3.2 Dense Data and Small Multiples

Tufte [45] describes the concept of small multiples as follows:

> "Well-designed *small multiples* are inevitably comparative, deftly multivariate, shrunken high-density graphics, usually based on a large data matrix, drawn almost entirely with data-ink, efficient in interpretation, often narrative in content, showing shifts in the relationship between variables as the index variable changes (thereby revealing interaction or multiplicative effects)."

Small multiples generally show how something evolves over time by showing only small changes between each multiple. The key point in this definition is that small multiples facilitate comparison. A viewer can easily scan small multiples and see how they evolve over time. This technique is very effective at breaking down dense data into small, comprehensible units.

3.3.3 Aesthetics

In addition to the overall organization of a visualization, there are a number of aesthetic design considerations that can have subtle effects on comprehension. One key design consideration is the dimensions of the visualization. The Golden Rectangle has a ratio of 1.0 in height to 1.618 in width. As a rule of thumb, data visualizations with aspect ratio close to this are preferable. Another key design consideration is line style. Lines should be thin and their value should be chosen in accordance with their position in the hierarchy of chart objects. For example, light gray lines should frame the visualization, while darker lines populate the foreground [44; 45].

3.4 Interaction and Plotting

As computers and the Internet became more popular in the 1990s, new methods for data visualization emerged. Shneiderman [43] describes many of these methods in his landmark paper *The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations*. In this paper Shneiderman [43] describes what he believes to be the most important principle in information visualization, the Visual Information Seeking Mantra: *"Overview first, zoom and filter, then details-on-demand"* [43]. To explore the implications of the Visual Information Seeking Mantra, it is worthwhile breaking it into parts and discussing each each one individually, as follows.

3.4.1 Overview

The main goal of the *overview* is to gain a notion of the entire collection of data that one is viewing. This is similar to the notion of the macro view of a micro/macro visualization discussed in Section 3.3.1. The overview generally contains an adjustable area that can be used to select a detail view which is similar to the notion of the micro view. Strategies typically employed to provide the detail view include zooming and fish-eying [43].

3.4.2 Zoom and Filter

The act of *zooming* is to focus in on certain items in a collection that are of interest. Making this action happen gradually allows the user to retain a sense of position which may be important when interpreting the data. To *filter* is to remove items that are not of interest. Both of these actions are often accomplished through the use of slides or buttons accompanying the graphic [43].

3.4.3 Details-on-Demand

The notion of *details-on-demand* is that a user can request more details about an item or group of items whenever needed. For this to happen the collection of items needs to be trimmed to a reasonable size so that individual items can be selected. Typically the selection of an individual item is accomplished by clicking or hovering on the item which results in a popup window [43]. Section 4.3.5 discusses how SAFE's visualization component handles forming collections that provide details-on-demand.

3.5 A Grammar of Graphics

The trend of twentieth century publications concerning graphics was to discuss them informally. Leland Wilkinson's *The Grammar of Graphics* [52] sought to formalize much of what had been previously discussed informally. Wilkinson sought to extend the notion of what makes up a graphic by formalizing grammatical rules for creating perceivable graphs. His grammar is a mix of mathematical and aesthetic rules. In this sense, the word *aesthetics* is not treated as a matter of taste, but rather by relating sensory attributes to abstractions. For a discussion of "taste" see Section 3.3. Although most of Wilkinson's grammar goes beyond the scope of this thesis, in the remainder of this section, I discuss important points that relate directly to my work.

3.5.1 Interactive Exploration

Wilkinson [52] defines two categories of exploratory controllers: indirect manipulation tools and direct manipulation tools. Indirect manipulation tools operate on a alternative representation of the graphic and not the graphic itself. Examples of indirect manipulation tools include sliders, buttons, and joysticks. Direct manipulation tools, which are generally preferred, operate on the graphic itself. This provides the benefit of the user not having to look away from the graphic when it is being manipulated.

One specific method for direct manipulation that is of interest in relation to my work is *brushing*. The act of brushing highlights objects contained within a certain region of a graphic. It can be thought of as dragging a paintbrush over a certain portion of the graphic and that portion changing its properties to reflect that it has been dragged over. Brushing as it relates to SAFE's visualization tool is discussed in more detail in Chapter 4.

3.5.2 Double Axes

A graphic with double axes is one in which a left and right vertical axis exist, each with their own scale. Double axes can serve one of two purposes: the axis can represent the same variable with two different scales or they can represent different variables. The latter purpose allows the viewer of the graphic to index one variable against another graphic element [52]. For example, one axis could scale a line representing the price of the S&P 500 while the other axis could scale a line representing the unemployment rate.

The main problem with graphics that utilize double axes is that the relative differences of the two scales can potentially create a deceptive graphic [52; 49; 51]. However, it is useful at times to compare two different series which have different units or which have the same units but different magnitudes. Wickham [51] identifies two techniques for dealing with this problem. The first technique, as demonstrated in Figure 3.8, is to rescale the variables to have a common range, such as $[0, 1]$. The second technique is to use *faceted graphics*, which stack, on top of one another, multiple plots that share the same x-scale, but not necessarily the same y-scale. This technique is an example of small multiples, discussed in Section 3.3.2. Figure 3.9 [51] shows an example of how faceted graphics can be used to represent series having very different magnitudes.

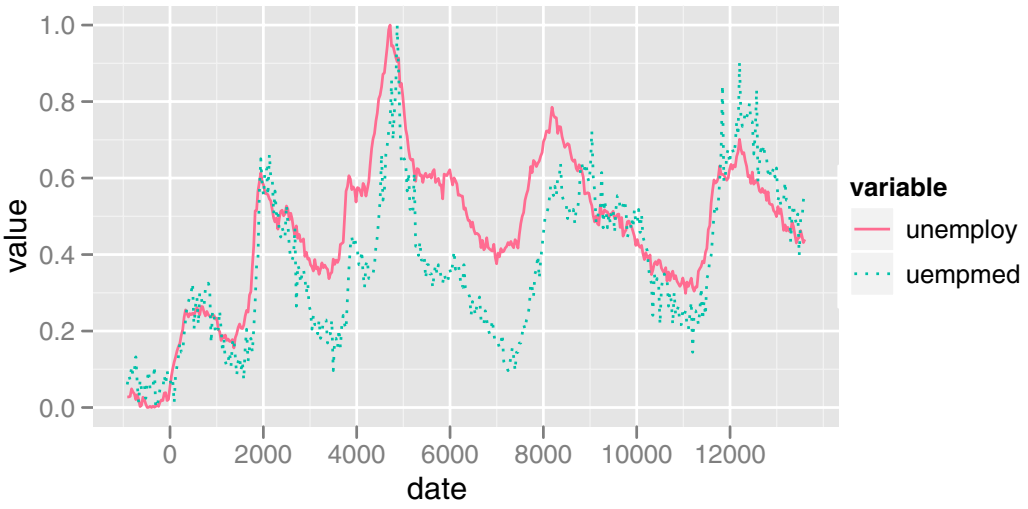


Figure 3.8: Two data series with the same units but different magnitudes plotted using [0,1] normalization.

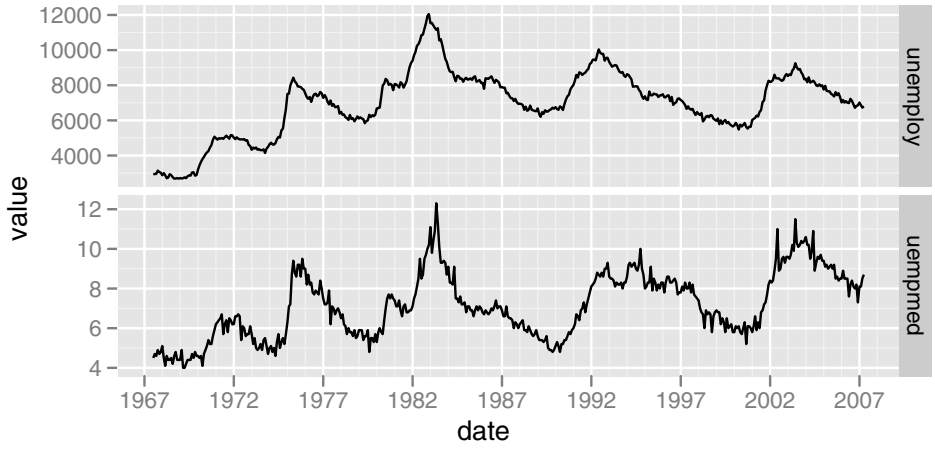


Figure 3.9: Two data series with the same units but different magnitudes plotted using faceting.

3.6 Chapter Summary

This chapter discussed the field of information visualization as it has evolved over the twentieth and twenty-first century. It analyzed the major contributions of Bertin [12], Tukey [46], Tufte [44; 45], Shneiderman [43], and Wilkinson [52]. All of these individuals helped to legitimize the field of information visualization. They also helped to develop best-practices which ensure that graphics are meaningful and credible. SAFE's visualization component was designed with the work of these individuals in mind.

Chapter 4

Design Considerations

There are many important considerations behind the design and the implementation of SAFE's visualization component. These decisions were all influenced both by the project goals of SAFE and by the best practices described in information visualization literature. Since information visualization is a young and rapidly growing field, many unanswered questions still arise when developing visualization tools. This chapter presents a range of issues that I confronted in creating SAFE's visualization component, some of them related to design, others related to practical aspects of software development.

4.1 Licensing

Licensing was a major consideration in the design of SAFE's visualization component. Since its inception, ns-3 has followed the GNU General Purpose License (GPL) version 2. For the sake of consistency with ns-3, SAFE follows the same licensing model, as established in the proposal for the grant that funds its development [1].

Developed by Richard Stallman and the Free Software Foundation, GPL version

2 was "designed to make sure that you have the freedom to distribute copies of free software (and charge for this service if you wish), that you receive source code or can get it if you want it, that you can change the software or use pieces of it in new free programs; and that you know you can do these things" [2]. GPL version 2 is not to be confused with the newer version of the license, GPL version 3. While all software released under GPL version 2 is compatible with GPL version 3, the reverse is not true.

To say that two licenses are compatible means that programs released under the two licenses can be combined into a larger work while still satisfying the requirement of both licenses. Due to SAFE's licensing requirement, all of the programs bundled within SAFE's visualization component needed to be released with a license that was compatible with GPL version 2. Such licenses include the Modified BSD license and the Mozilla Public License (MPL) version 2.0 [3], to name a couple.

4.2 Platform

When it comes to building a tool for data visualization, there are two main software platform options: a personal computer or web. Both platforms have advantages and disadvantages, which need to be considered when evaluating them for development. In general, personal computer tools have better support for hardware accelerated graphics and can run as standalone applications. Unfortunately, in this type of setting, tools are often dependent on the installation of other software, which complicates deployment and maintenance.

Web applications, on the other hand, are very easy to maintain, and work on any system that has a web browser. They are also well-suited for interactive applications that have numerous graphics. Since SAFE's experimental configuration front-end was conceived with the web platform in mind, it made the most sense to also develop the visualization component for the same environment.

4.3 Interactive Graphics

Through the lessons learned from the literature discussed in Section 3.5.1, I concluded that there would be benefit in creating an interactive view of simulation results. Also, the background research in Section 3.3.1 inspired the decision to make this view offer a micro/macro time-series graphic of the *entire data set* generated by the experiment's execution. Figure 4.1 shows such a graphic with many of the components labeled. The user can select multiple metrics through an intuitive interface. Clicking on a non-highlighted metric name (within an automatically populated metric list) causes that metric to become highlighted with its graphic color and then plotted. This can be done for multiple metrics.

An overview graphic with a visual slider, often called a *brush*, is placed directly below the main graphic, a technique commonly referred to as *overview plus detail*, or *context plus focus* [43]. Such a graphic allows the user to see how a metric evolved over the course of the experiment, compare it to another metric, and then zoom into to as little as a single data point. The act of zooming in using the overview graphic is called brushing and is discussed in more detail in Section 4.3.4.

4.3.1 Relevant Technologies

I found that numerous technologies proved essential when developing the interactive visualization component for SAFE. These technologies range from the widely adopted to the experimental, with each of them being specifically suited for developing a functional, interactive presentation layer. One specific concern relating to all of these technologies is that they are rapidly changing. For this reason, I sought out technologies that promote backwards compatibility and well-documented updates.

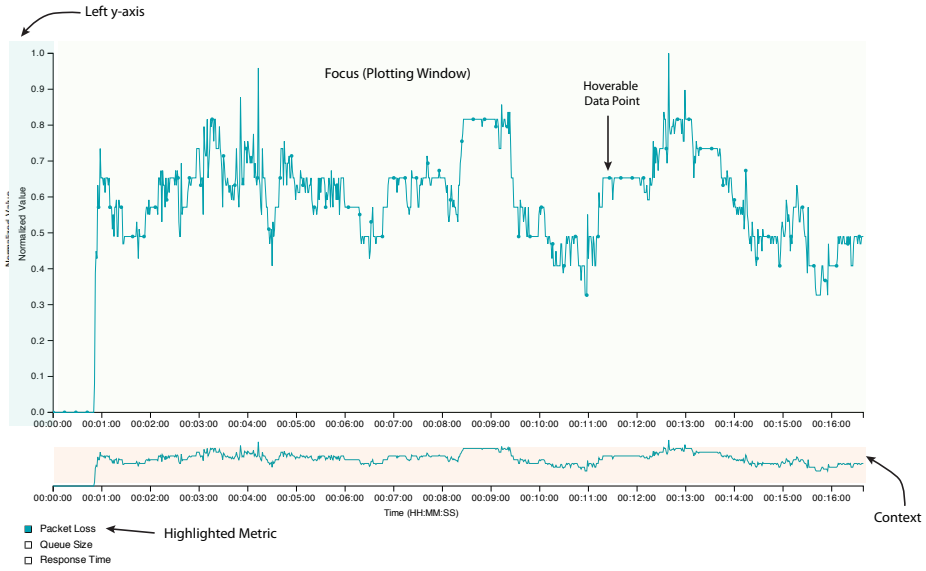


Figure 4.1: Labeled Context Plus Focus Graphic.

HTML

Of all of the technologies associated with the web, the HyperText Markup Language (HTML) is arguably the most important. HTML is a markup language used to describe the structure of webpages. It was first drafted in 1992 by Tim Berners-Lee, and has since gone through many incarnations, with the most recent being HTML5 [40].

In HTML, content is surrounded by *tags* which generally denote the semantics of the content. For example, a paragraph in HTML always begins with a `<p>` tag, referred to as an *opening* tag, and always ends with a `</p>` tag, referred to as a *closing* tag. Similarly, the largest heading on a page always begins with a `<h1>` tag and always ends with a `</h1>` tag. There are also self-closing tags such as the `<img>` tag. These tags to do not require closing tags such as `</p>` and `</h1>`. Through the use of these tags, a web developer can craft a page that can be viewed in a web browser such as Google Chrome, Mozilla's Firefox, Apple's Safari, or Microsoft's Internet Explorer.

CSS

In the web's infancy, HTML was the king of web development languages. As websites and their designs became more complicated though, HTML started to be used in ways that went against the ideals of its creators. As a markup language, HTML's purpose is to describe the roles of elements in a document. In the early-1990s, as the number of websites grew, developers began to ignore the semantics of HTML's tags. The general practice at this time was to structure web pages using HTML's `table` element. Code for such pages quickly became illegible, as the tags were being used in ways that were not intended. The `table` element was developed to contain tabular data, not to define the style of webpages. Thus, HTML quickly became a tool for not only describing the roles of elements in a web page, but also describing the style of a web page.

By the mid-1990s many developers began to realize that betraying the semantics of HTML and using it to describe the style of a page was a serious problem. In 1996, Håkon Wium Lie and Bert Bos proposed a solution to this problem. Their solution, named Cascading Style Sheets (CSS), allowed developers to separate the structural system (HTML) from the presentational system (CSS). Developers could create one stylesheet that would define the how their pages would look, and could easily change the style of their entire website by editing one file [32].

CSS plays a critical role in modern web development, especially development of interactive applications. The introduction of CSS3 put a whole new set of tools in developers' hands. CSS3 styles are capable of doing 2D and 3D transformations, rounded corners, and transitions. Since the CSS3 standard is being modularly developed, new functionality is being added every year. Once fully implemented, these tools will allow for better looking, more interactive web pages [48].

JavaScript

JavaScript [22] is an object-oriented, interpreted language with syntax similar to C. It is also one of the most widely used client-side scripting languages. While JavaScript gained its popularity through its use in client-side scripts, it is now being used in a variety of applications. Node.js [5], a popular event driven networking engine, has brought the power of JavaScript to server-side applications. This allows developers to use one language for their entire project, with both client and server-side scripts being written in JavaScript. Such a development model has attracted major industry players such as LinkedIn [24] and Microsoft [11]. This makes JavaScript an invaluable tool for any front-end or back-end web developer [21].

Modern web applications are expected to be responsive, interactive, and visually interesting. JavaScript allows developers to achieve all three of these goals. Browser developers have also worked hard to make sure that their applications have powerful JavaScript engines that are quick and consistent. Both Google and the Mozilla Foundation have invested large amounts of resources in developing such engines. In fact, both Google Chrome's V8 engine and Safari's Nitro engine compile JavaScript rather than interpret it, which allows the code to be executed as native machine code as opposed to bytecode running on a virtual machine. This allows even extremely complex client-side applications to achieve excellent performance [47].

SVG

Scalable Vector Graphics (SVG) is an XML-based language for describing and animating two-dimensional graphics. A major advantage of SVG is that, like HTML, all elements of an SVG graphic have corresponding objects in the Document Object Model (DOM). This allows SVG objects to be dynamically manipulated using JavaScript, which is necessary for creating interactive graphics. As its name implies, SVG is also vector-based. Unlike raster, or pixel-based, graphics which are commonly stored in a format such as JPEG or Graphics Interchange Format (GIF), SVG-based

graphics can be scaled to any size without noticeable quality loss. The combination of these benefits makes for scalable, interactive graphics that are viewable in any web browser [14].

D3.js

D3.js [13] is open source and JavaScript-based, developed after years of research into best practices in visualization. One major advantage of D3.js is that it utilizes SVG for graphics, which can be resized and zoomed to any resolution without noticeable quality loss. SVG based graphics also have the advantage of having a well defined structure that can be easily converted into other commonly used vector formats. Both of these factors are significant advantages of SVG-based plotting libraries over ones that utilize the HTML5 canvas element.

Django

Django is an open source, Python-based web development framework that follows the model, template, and view (MTV) design pattern [29]. This design pattern is very similar to the popular Model-View-Controller (MVC) design pattern which is commonly known for its use in iPhone application development. Two driving philosophies behind both MTV and MVC design patterns are loose coupling of components of an application and strict separation between pieces of an application.

To understand how Django serves the purposes of SAFE's visualization component, it is useful to have a bit of background on the MTV design pattern. The 'M' of MTV stands for **Model**, which is the data access layer of an application. This layer abstracts interaction with the underlying database into easy to use functions. This removes the confusion that often arises when developers try to interact with a database using a language such as Structured Query Language (SQL). Since a crucial part of SAFE's visualization component is querying the database for simulation

results, having this abstraction is very convenient.

The 'T' of MTV stands for **Template**, which is the presentation layer of the application. A template is code that can be rendered by a web browser, such as HTML or SVG, with placeholders throughout it where content can be dynamically injected. This content is injected by the **View**, which is the 'V' in MTV. The View is the business logic layer which interacts with the Model, bringing data into the Template. It is useful to think of the View as a bridge between the Model and the Template. Much of SAFE's web interface needs to be dynamically generated based on what the user is currently doing, making a framework such as Django useful.

I chose Django over other web frameworks when building SAFE's web user interface because it is the most powerful, general-purpose web framework written in Python. The Django-based web user interface integrates seamlessly with the core backend of SAFE which is written in Twisted, a Python based networking engine [20]. This ultimately makes for cleaner code that is easier to extend.

4.3.2 Data Interchange

Django is excellent for querying SAFE's database for simulation data, but a method for interchanging data between Django and D3.js was still needed. A common method of interchanging data for web-based plotting is JavaScript Object Notation (JSON). JSON allows for the serialization of a data structure which can subsequently be transmitted within or between applications. A major advantage of JSON is that it can easily be parsed into a JavaScript object which can then be plotted.

While JSON would have worked well for the interactive data visualization component, I decided that the comma-separated values (CSV) format would be a better solution. While JSON works for a variety of data types, CSV is designed solely for tabular data. Since all of the data coming from SAFE's database to the plotting component is tabular, the CSV format is an adequate solution.

What gives CSV an edge over JSON is its compatibility with many other plotting tools. Having SAFE's interactive plot driven by the CSV format enables the data to be easily be downloaded for plotting with other software packages. With this feature, power users can download data and plot it using tools as Excel, MATLAB, or `gnuplot`.

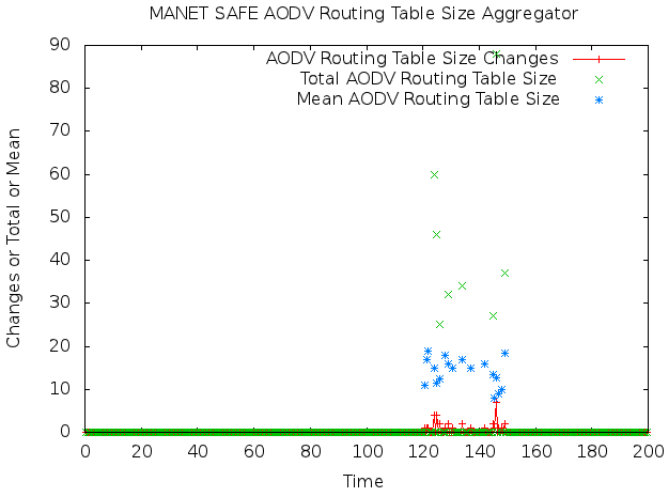
4.3.3 Data Binding and Scaling

I also found it important to develop a method to scale multiple data series which may have either different magnitudes or units. While this may seem like a minor point, improper scaling can lead to a plot that is difficult to interpret, potentially leading to wrong conclusions. Figure 4.2a shows an example of a plot with three series of varying scales. The series in green is sufficiently large that it begins to overwhelm the other two series. In extreme cases, such as in Figure 4.2b, one series can completely overwhelm the others, making an uninterpretable plot.

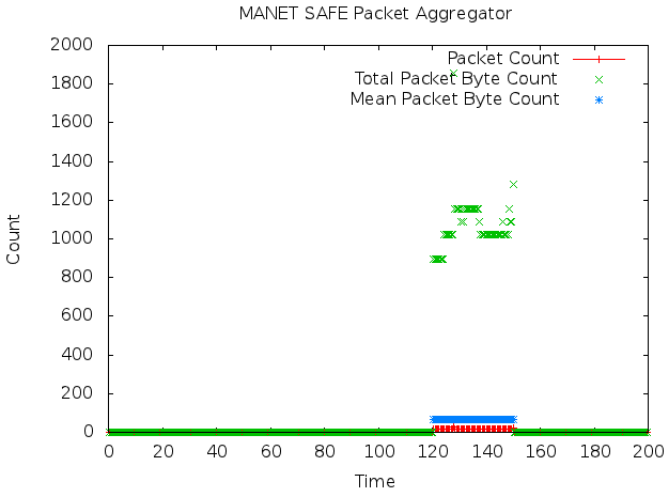
When the interactive time-series visualization tool is started, there is one blank left y-axis as shown in Figure 4.3. When a user decides to plot a new metric, the plotting system first checks whether another data series is currently plotted on the graphic. If no other data series is currently plotted on the graphic, then the metric is plotted as a solid line. If another data series is already plotted on the graphic, then the metric is plotted as a dotted line.

To handle the problem of differing magnitudes discussed in Section 3.5.2, I choose to scale all metrics to a common scale. A metric's data is represented by a set $D = \{d_0, d_1, ..., d_n\}$ where each d_i is a data point. The maximum data point in D is D_{max} and the minimum data point is D_{min}. D can then be normalized between 0 and 1 by computing the following for each member of D:

$$N(d_i) = \frac{d_i - D_{min}}{D_{max} - D_{min}}$$



(a) Moderate Scale Differences



(b) Major Scale Differences

Figure 4.2: Plots exhibiting various scale differences.

Figure 4.3: Empty plot when tool is initialized.

This method normalizes all the data series added to the plot, which prevents any data series from being overwhelmed by the others. While supported in the literature, this method produces the same plot as using double y-axes with maximal scale. Likewise, the faceting technique described in Section 3.5.2 still has issues with decipherability. Exploring additional ways to plot multiple metrics on the same plot in a more interpretable way is planned as future work.

When the user removes metrics from the plot, I decided that the graphic should preserve the line type and color of any lines remaining on the graphic. I found this approach to be more intuitive than redrawing the remaining lines as if they were originally drawn on a blank graphic. It also follows from Wilkinson's notion that the graphic frame either does not change or changes in a way that is expected and consistent [52].

4.3.4 Brushing

As discussed in Section 3.5.1, brushing plays a critical role in the interaction between the user and SAFE's interactive plotting component. SAFE's interactive plotting component is a direct manipulation tool and brushing is used to select which data is currently being viewed in the focus graphic. The brush is dragged over the context graphic to highlight a portion of the time-series for closer inspection. The brush can be interactively expanded or dragged after it has been created to give the user finer control over what to display in the graphic.

4.3.5 Hoverable Data Points

While a line on a time-series graphic can give a great indication of trends in the data, in most cases there is also value in investigating specific data points. Unusual features of the graphic and outliers may need to be analyzed individually, and thus having some way of getting data back out of the line after it is plotted is quite useful.

To facilitate the observation and analysis of singular data points, what Shneiderman [43] calls *details-on-demand*, I implemented hoverable data points, as seen in Figure 4.1. These points are bound directly to the underlying data series and are updated along with the plotting window. When a user hovers over one of these data points, its x and y-value are displayed next to the point. The point is also enlarged when hovered over to indicate to the user which particular data point they are currently viewing. As soon as the user removes his/her cursor from the data point, the x and y-value fade away and the point goes back to its normal size.

A common characteristic of most simulations being conducted with SAFE is the high volume of data they generate. Since a micro-macro graphic provides a view of the entire zoomed-out data set in one window, it also provides a view of possibly thousands of hoverable data points. Cramming all of these points into a single view would make an incomprehensible graphic. The number of hoverable data points being

plotted could easily outnumber the number of pixels to plot them. Since a pixel is the smallest unit of manipulatable area on the screen, it is not possible to cram more than one point into one pixel.

Instead of trying to cram an incomprehensible amount of hoverable data points onto the screen at once, I developed a method for dynamically scaling the density of points in the current plotting window. This metric will only show a hoverable data point when it is separated from other hoverable data points by enough pixels that it can be easily distinguished and interpreted.

Value-based Point Density Scaling

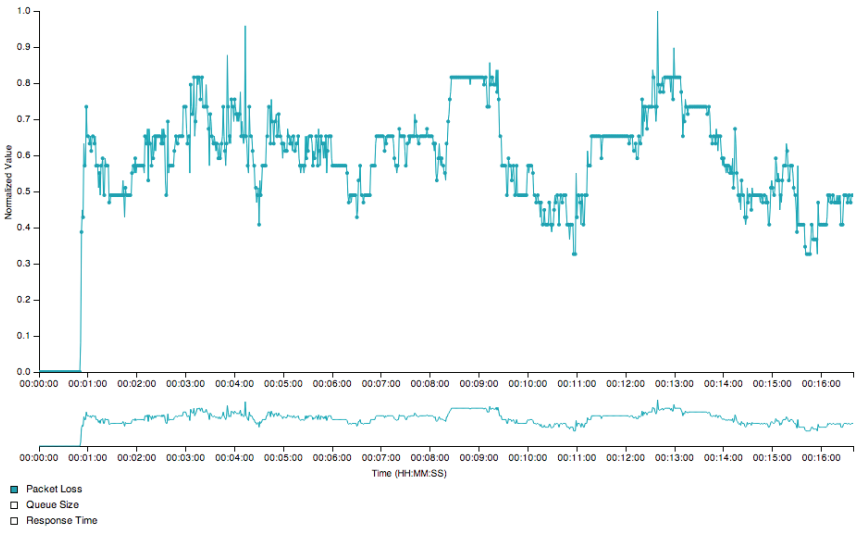
The initial method I developed for dynamically adjusting hoverable point density relies solely on the amount of horizontal spacing h that each hoverable point needs to be distinguished from surrounding hoverable data points. Figure 4.4 show how various values for h affect the graphic. From these tests I determined an appropriate value for h to be around 6. In the future I plan to expose this parameter to the user, giving them a finer control over the graphic.

To understand how h is to be used, one must first understand how data is represented by the plotting tool. Each graphic is composed of a set of lines $L = \{l_0, l_1, l_2, ..., l_k\}$. A line l_k composed of n data points is represented by a set D such that:

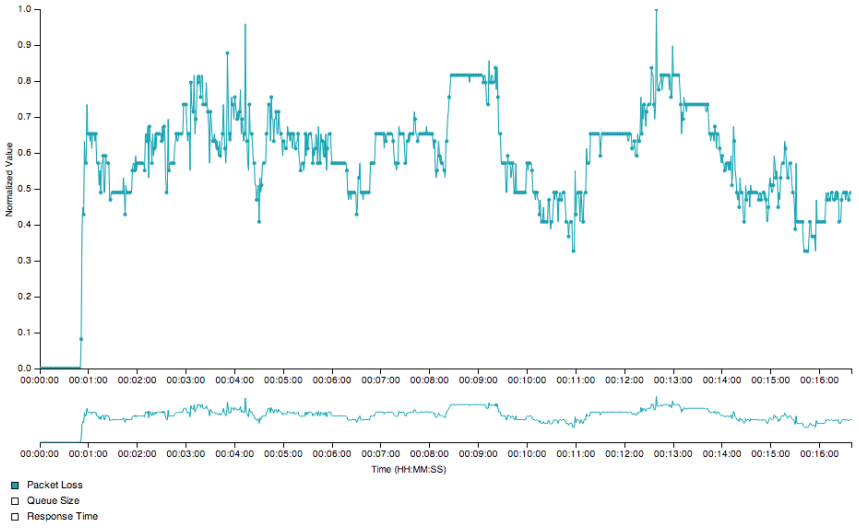
$$D = \{p_0, p_1, p_2, ..., p_{n-1}\} \text{ where } p_i \text{ is a pair } p_i = (x_i, y_i)$$

The final set of hoverable points H is simply a subset of D:

$$H \subseteq D$$



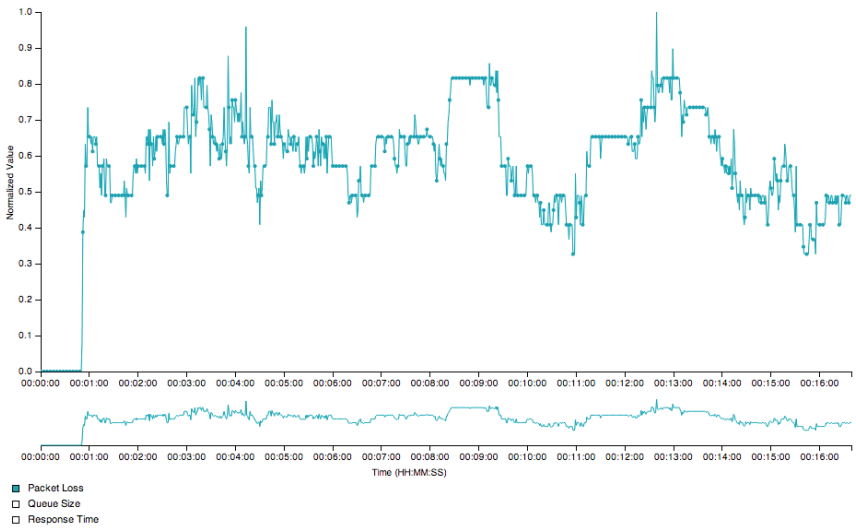
h = 1



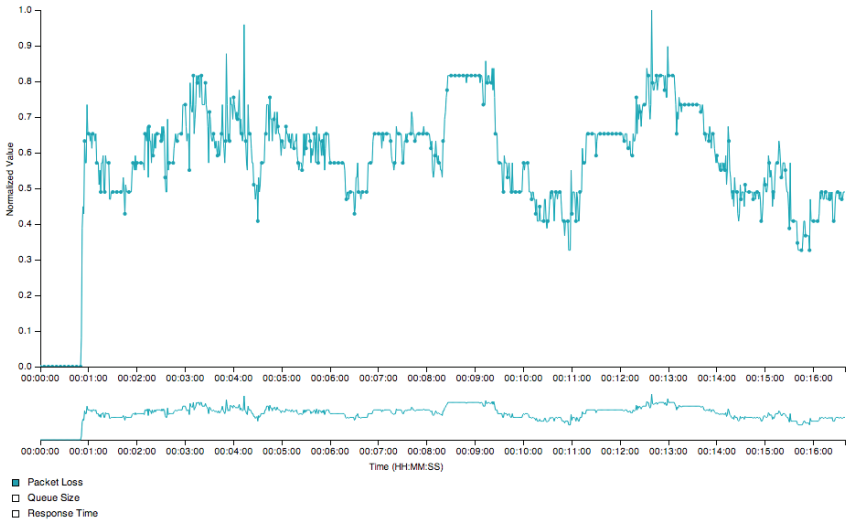
h = 2

(a)

Figure 4.4: Comparison of how different values for h affect graphic presentation.



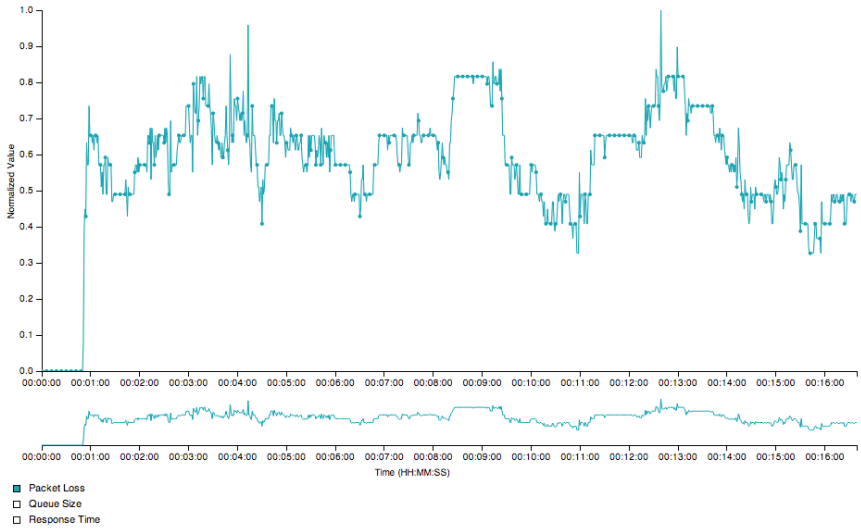
h = 3



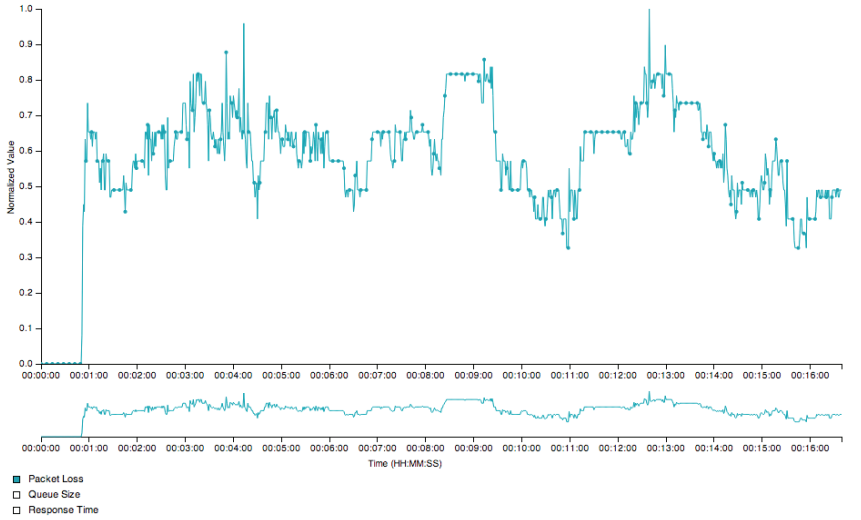
h = 4

(b)

Figure 4.4: Comparison of how different values for h affect graphic presentation.



$h = 5$



$h = 6$

(c)

Figure 4.4: Comparison of how different values for h affect graphic presentation.

Whether a certain point p should be hoverable, and thus be in H, can be determined iteratively using h as follows. The first hoverable point is always p_0 as it is the first point that is viewable in the plotting window, and thus it is added to the set H. The points $p_1...p_n$ are then examined in order, looking for the first p_i where $x_i > h \times |H|$, we will call this point p_z. When $p_z \in D$ is found it is added to the set H and the search begins again from $p_z...p_n$. The process terminates when $z \geq n$.

After this process terminates, all the points in H are hoverable. If a graphic has multiple lines such that $|L| > 0$, $H_{l_0}...H_{l_k}$ can be determined and each line will be have hoverable points of appropriate density bound to them.

While this technique handles data that was not uniformly sampled very well, it is not the most aesthetically pleasing when brushing the graphic. When using this method, the hoverable points tend to disappear and reappear as the graphic is brushed, as if the hoverable points were flowing over the line. This can be both visually distracting and also frustrating if one is trying to follow a single glyph. Wilkinson [52] suggests making glyphs "move as a flock" so they are easier to track. To make this happen a new approach for scaling point density had to be developed.

Index-based Point Density Metric

In an attempt to develop a more aesthetically pleasing method for point density scaling, I utilized the following two aspects of the current graphic: the graphic window width w and the number of points n in a specific line's current domain.

In addition to the above two graphic parameters, a tweaking parameter p which represents the number of pixels desired for each point is used to determine m using the following formula:

$$m = \lceil \frac{n}{w} \times p \rceil$$

Thus, if a particular line had 500 points that were eligible to be hoverable in the

current window, the window had a width of 900 pixels, and the user wanted to plot 10 pixels per point, m would be 6. Figure 4.5 shows how various values for p affect the presentation of the graphic. From this figure I determined an optimal value for p to be around 8. Again, in the future I plan to expose this parameter to the user.

After m is calculated it can be used in the following manner. Again, each graphic is composed of a set of lines $L = \{l_0, l_1, l_2, ..., l_k\}$. A line l_k composed of n data points is represented by a set D such that:

$$D = \{p_0, p_1, p_2, ..., p_{n-1}\} \text{ where } p_i \text{ is a pair } p_i = (x_i, y_i)$$

The final set of hoverable points H is simply a subset of D:

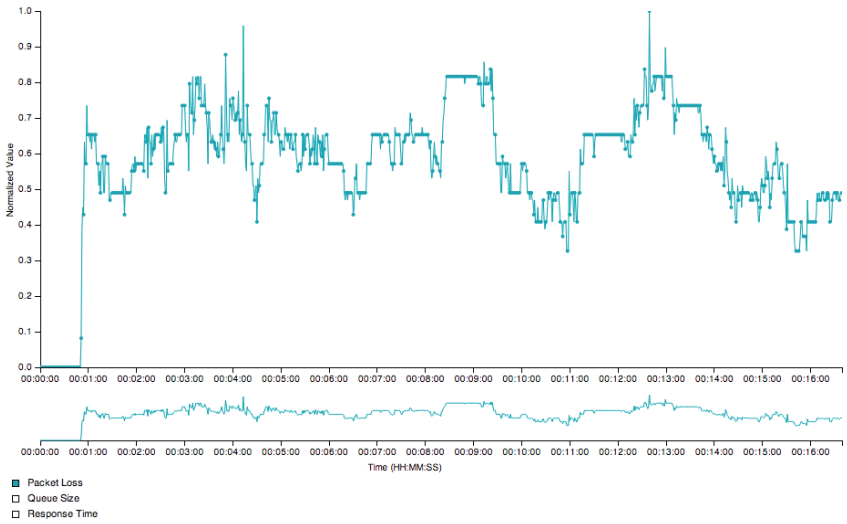
$$H \subseteq D$$

We can use m to determine if a certain point $p_i w$ should be hoverable as follows:

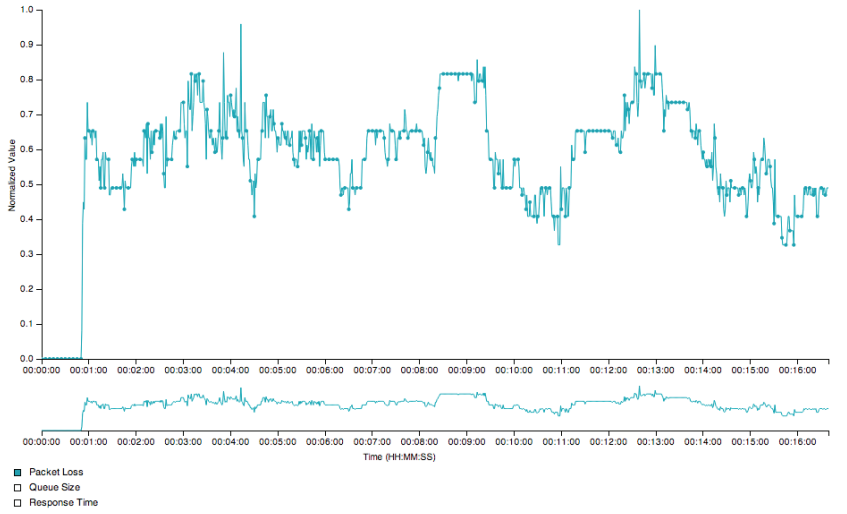
$$V(p_i) = i \pmod{m}$$

If $V(p_i) = 0$ then the point is added to H, otherwise it is not hoverable and thus not added to H. Thus, H is built iteratively by applying this criterion on each element of D.

This method works very well for uniformly sampled data and also is aesthetically pleasing when brushing. Unfortunately, it does not handle non-uniformly sampled data very well, especially data that is very sparse with high density clusters.



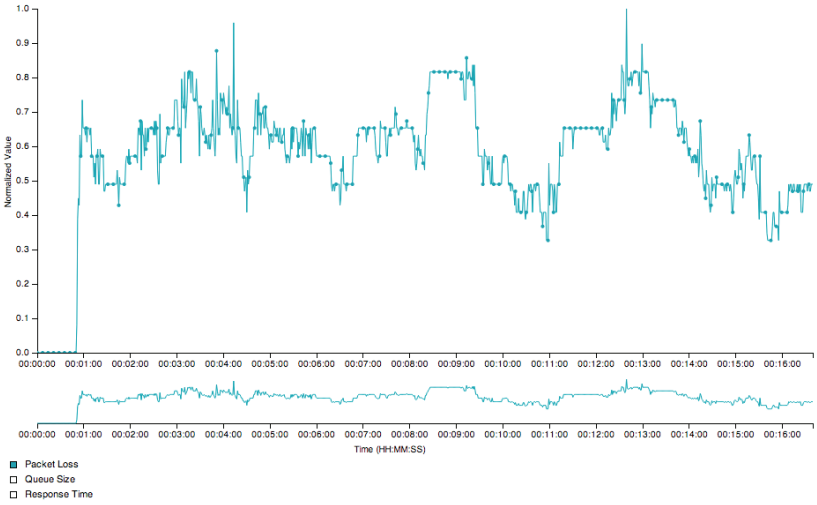
p = 2



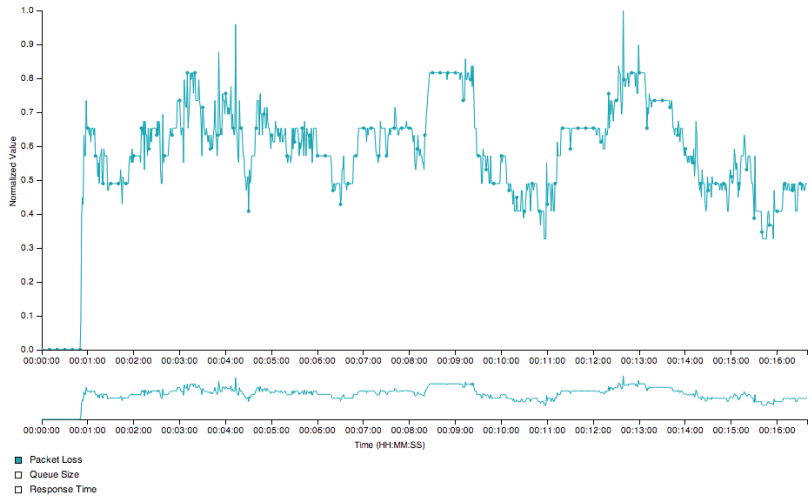
p = 4

(a)

Figure 4.5: Comparison of how different values for p affect graphic presentation.



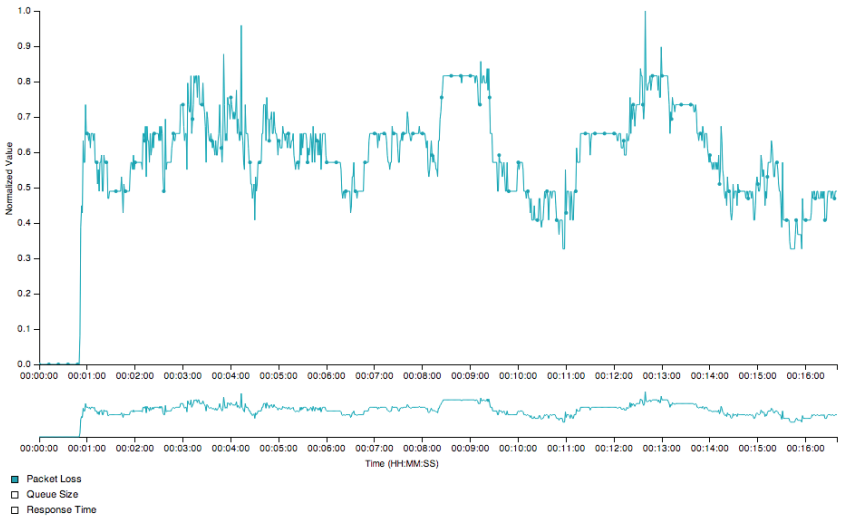
p = 6



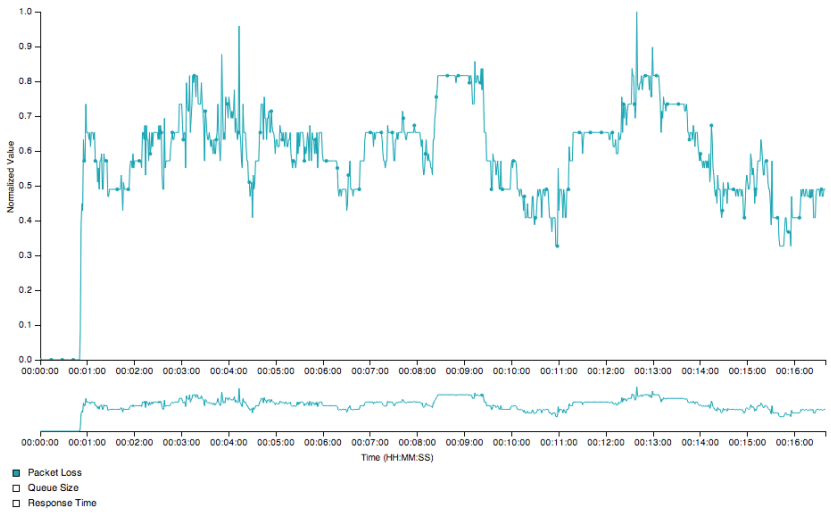
p = 8

(b)

Figure 4.5: Comparison of how different values for p affect graphic presentation.



p = 10



p = 12

(c)

Figure 4.5: Comparison of how different values for p affect graphic presentation.

Combined Point Density Metric

Both the value-based and index-based methods for point density scaling worked well for the majority of cases, but unfortunately they both had minor flaws that made them unsuitable for SAFE's application. It turns out that when combined though, these methods offset each others' flaws, making a graphic which has easily trackable glyphs.

Combining the two methods works as follows. First, the index-based method is applied, resulting in a set of hoverable data points H_i. The value-based method is then applied to H_i which results in a new set H_f. This is the final set of hoverable data points.

Another advantage of this method is that it accounts for scaling the density of points on lines that have different domains in the current plotting window, as shown in Figure 4.6. In this case the index-based metric by itself may leave high density clusters of hoverable data points in certain areas. The value-based method can then pass over these clusters and prune them to the correct density.

4.4 Static Graphics

While an interactive graphic is great for exploring relationships in data, it is not appropriate for publication. With static graphics, a more experienced user can have a finer degree of control over what the graphic looks like, while still conforming to the considerations outlined in Chapter 3. Another advantage of the static plotting mechanism is that it encourages the use of vector-based graphics. While SAFE's interactive plotting component utilizes SVG-based vector graphics, these graphics are not straightforward to export and save in a vector-based format. SAFE's static plotting component displays static graphics in the browser using the Portable Network Graphics (PNG), which is not vector-based. However the graphics are also down-

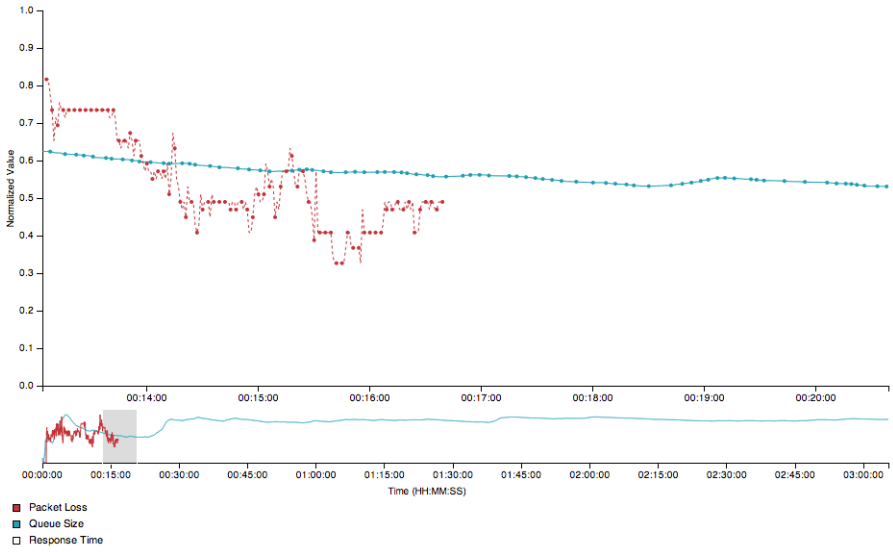


Figure 4.6: Lines with different domains still have properly scaled hoverable point density.

loadable in Portable Document Format (PDF) which is vector-based. These vector graphics ensure that blurry, eligible plots are not included in publications.

4.4.1 Relevant Technologies

I used many technologies in the construction of SAFE's static visualization component. The main purpose of using these technologies was to bring the power of desktop plotting tools to the web. In addition to the following technologies, Django, which is described in Section 4.3.1, also plays a critical role in generating SAFE's static graphics.

R

R is a free programming language that is tailored for data manipulation and analysis. Much of the inspiration for R came from the S programming language which was developed by AT&T in the late 1970s. While S has become proprietary, R remains free and has a large community of developers supporting it. For this reason R has become one of the most popular languages in use by data analysis professionals today [34].

R implements both object-oriented and functional programming paradigms which make it very flexible. Code written in R is generally very clean and understandable, as well as efficient. R was chosen for this project for all of the above reasons, in addition to the numerous amount of open source libraries that have been written for it. R can be thought of as the data processing backend to SAFE's static visualization tool.

ggplot2

Of the many great open source libraries for R, ggplot2 ranks among the most popular and useful. While a base installation of R includes graphic production functionality, ggplot2 is much more powerful and flexible. At its heart, ggplot2 is based directly on Leland Wilkinson's *The Grammar of Graphics* [52], allowing it to be used to produce nearly any kind of information graphic imaginable. These characteristics led to my decision to use ggplot2 as the sole mechanism to generate SAFE's static graphics.

rPy2

While R is a perfect candidate SAFE's static plotting backend, it is not necessarily easy to integrate code written in two different languages, such as R and Python. Given that SAFE's backend is written in Python this presented a problem. Luckily others have also realized a need for integrating Python code and R code and rPy2 [25]

was created. rPy2 provides a bridge between Python and R, allowing R code to be written and called from directly within a Python program. Since ggplot2 is a library for R all static plotting could be done through this bridge with the results being passed into the web user interface.

4.4.2 Extendability

SAFE's static plotting component was designed specifically to be flexible and extendable. While the code driving SAFE's interactive visualization component is on the order of thousands of lines for one graphic, the amount code for most static plots is less than five lines. This makes it very easy for both SAFE's maintainers and users to add new types of static graphics.

Future work includes developing a mechanism for users to craft new graphic types through the web user interface. After selecting experimental data, the user would be presented with a form with a variety of plotting options. The user could then customize these options and be presented with a graphic that fits their specific needs. This mechanism could also drive the generation of static graphics for power users who do not desire to use SAFE's web user interface.

4.5 Open Source Tools for Data Visualization

In constructing SAFE's data visualization component, I evaluated many other plotting tools that could have been helpful. While some of these tools aligned with the goals of SAFE, they were not licensed in a way in which they could be incorporated into SAFE. Many of these tools acted as inspiration for SAFE's visualization component, showing what works well and what does not for interactive visualization. Comparing the approaches of these tools to the points discussed in Chapter 3 guided many of the decisions previously discussed in this chapter.

4.5.1 Shiny

Shiny is a tool for R which allows R-based graphics to be displayed and interacted with through a web browser [42]. The basic functionality of Shiny is very similar to SAFE's static plotting tool, but Shiny is much more flexible and extendable. Instead of using a bridge between R and Python like SAFE, Shiny is written purely in R. Shiny gives the option for developers to either write their interactive graphics in R or HTML, CSS, and JavaScript. This makes Shiny work well for both statisticians and web developers. Shiny would have been very helpful in the development of SAFE's visualization component, but unfortunately it is licensed under GPL version 3 which is not compatible with GPL version 2 as discussed in Section 4.1.

4.5.2 Google Chart Tools

Google Chart Tools is an application programming interface (API) for displaying interactive charts in a web browser [6]. It supports numerous chart types including line charts, pie charts, scatter charts, area charts, and bar charts. Google Chart Tools' line graphic is similar to the focus graphic in SAFE's interactive visualization component. However, one notable difference is that hoverable points are not displayed on the line, and only appear when hovered over.

Since Google Chart Tools is an API and not a library, it could be used within SAFE's visualization component without any licensing issues. However, the major drawback of Google Chart Tools is that the user must be connected to the Internet for it to function properly. The code to create the graphics is located on Google's servers, and thus the graphics cannot be generated unless a connection can be made between the user's computer and Google's servers. Since no other portion of SAFE relies on an Internet connection to function, it would not be ideal to require one for the visualization component. For this reason I choose not to use Google Chart Tools, instead opting for a local library that is more flexible.

4.5.3 googleVis

Related to Google Chart Tools is the googleVis [26] library which is an interface between R and Google Chart Tools. The major advantage of googleVis over traditional use of Google Chart Tools is that googleVis does not require one to upload their data to Google's servers to have it visualized. With googleVis the graphics are generated locally, but still require Internet access for use of Google's API. The main use case which googleVis was developed around was for analysts and statisticians who already knew R but did not necessarily have expertise in creating web-based information graphics. I took a similar approach when creating SAFE's static visualization tool. Unfortunately SAFE could not leverage googleVis because it is licenced under GPL version 3, which makes it incompatible with the rest of the project.

4.5.4 NVD3

Developed as an extra layer of abstraction on top of D3.js, NVD3 [7] provides a variety of pre-built graphics, including one for context plus focus time series. The graphics in NVD3 are similar to those created for SAFE's interactive visualization component, only more general purpose. NVD3 handles hoverable data points similar to Google Chart Tools where they are only displayed when hovered upon by the user. The context plus focus graphic also differs from SAFE's in that it adaptively scales the left y-axis based on the data in the current plotting window. I chose not to include this in SAFE, as it has a similar distortion effect as having multiple y-axis, as discussed in Section 3.5.2. Another aspect of NVD3 which restricted its use in SAFE's visualization component is its license. NVD3 is licensed under Apache Version 2.0, which is compatible with GPL version 3, but not GPL version 2 [3].

4.6 Chapter Summary

Many of the design considerations for SAFE's visualization component were discussed in this chapter. These included issues involving licensing, selecting the proper platform, scaling the density of points on a graphic, and making an extendable tool, just to name a few. Each of these decisions were made with the issues from Chapter 2 and the best practices from Chapter 3 in mind. The big picture design consideration to take away from this chapter is that SAFE's visualization component was designed to be powerful yet user-friendly while supporting credibility in network simulation research.

Chapter 5

Case Studies

To test the performance of SAFE's visualization component, I subjected it to a variety of common use scenarios. These scenarios include making graphics which have time series of very different magnitudes, comparing two series where a causal relationship may or may not exist, and generating graphics for publications. While these scenarios do not cover all of the functionality and use cases of SAFE's visualization component, they represent areas where mistakes are usually made. Through these case studies I show that SAFE's plotting tool helps to avoid common mistakes.

5.1 Exploration, Comparison, and Magnitude

One mistake that is commonly made when generating graphics is plotting series which have either very different magnitudes or different units entirely. As described in Section 4.3.3, SAFE mitigates this issue by normalizing the data series so that they have a common scale. This makes the y-axis unitless, but by hovering over data points the user can still retrieve values with their corresponding units.

Comparing Figure 5.1 and Figure 5.2 shows how normalizing the data can be

useful. In Figure 5.1 the scale of the red series completely dominates the scale of the blue series. This makes comparison of the series impossible. Figure 5.2, on the other hand, shows how SAFE's interactive plotting component handles the same series. By normalizing the values, SAFE's interactive plotting component allows users to compare the series and look for interesting relationships. Figure 5.3 shows how brushing can further aid in discovering relationships.

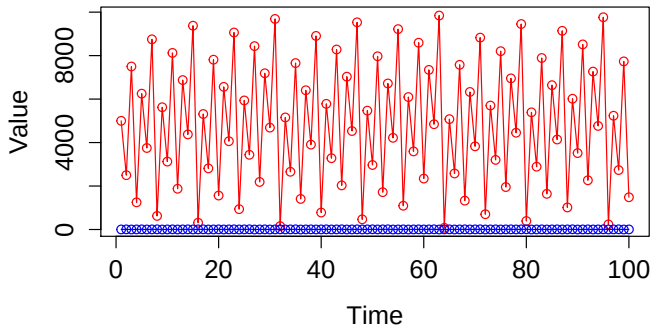


Figure 5.1: Data series exhibiting scale differences without normalization.

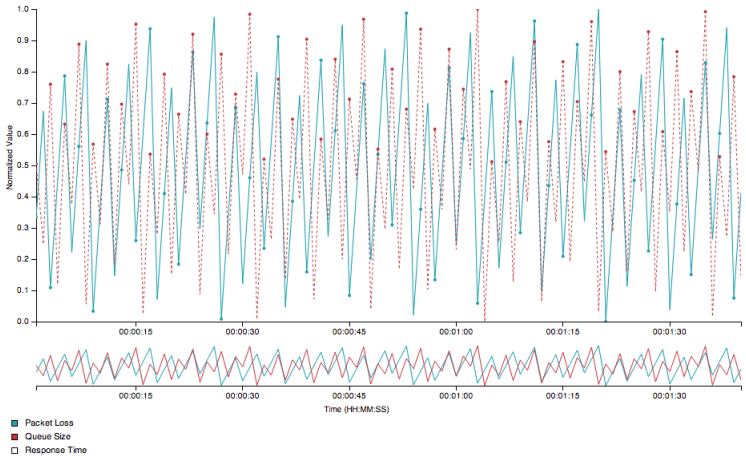


Figure 5.2: Data series exhibiting scale differences plotted with SAFE's interactive visualization component.

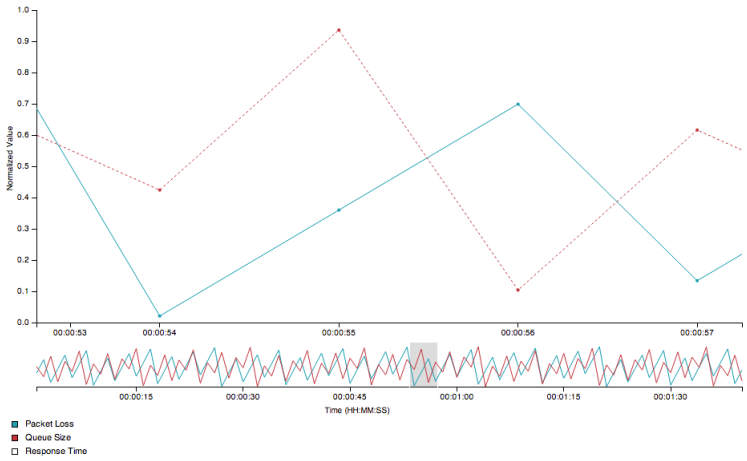


Figure 5.3: Data series exhibiting scale differences plotted with SAFE's interactive visualization component, brushed.

5.2 Creating Graphics for Publication

For many researchers, the final step in the SAFE workflow is the generation of graphics for publication. In general, plots such as Figure 5.1 are not appropriate for publication for lack clarity and decipherability. The simplest use case for SAFE's static plotting tool is that of a single time series. This type of plot is shown in Figure 5.4, which avoids the pitfalls identified in Pawlikowski et al. [37]. It also follows all of the design guidelines and best practices identified in Chapter 3.

If a user wishes to compare different time series, they have the option of either creating a faceted graphic or normalizing the data before plotting. The results of these choices can be seen in Figure 5.5. Both these plots adhere to the goals of SAFE and all the best practices in visualization mentioned throughout this thesis.

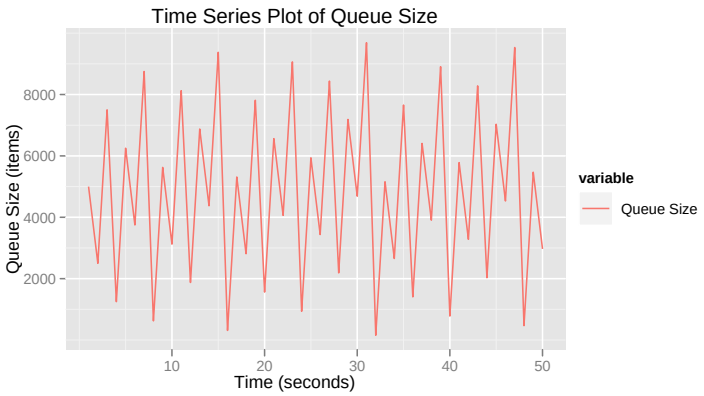
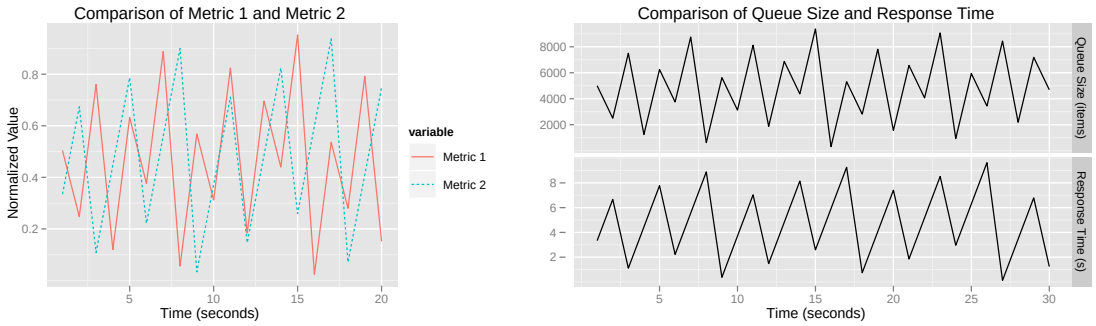


Figure 5.4: Single time series data series plotted with SAFE's static visualization component.



(a) Normalization (b) Faceting

Figure 5.5: Graphic demonstrating both options for dealing with different magnitudes and units.

5.3 Chapter Summary

This chapter discussed the most common scenarios for which SAFE's visualization component will be used and showed how it performed in such scenarios. These scenarios include time series data of different magnitude or units, comparing time series,

and generating static plots for publications. For all of these scenarios, SAFE's visualization component produces graphics that adhere to best practices in both network simulation methodology and the creation of information graphics.

Chapter 6

Related Work

Numerous tools with goals similar to SAFE exist, both inside and outside the field of network simulation. Some of these tools, such a SimProcTC, have integrated plotting mechanisms into the core of the tool [18]. Other tools, such as James II, have numerous communal projects which seek to support various types of information visualization [33; 28]. The fact that these tools exist and realize the importance of data visualization in output analysis gives credibility to the development of such a tool for SAFE. Furthermore, my work builds upon many of the ideas presented in the visualization components of these tools.

6.1 SimProcTC

SimProcTC [18] is a tool-chain developed to automate much of the work involved in performing OMNeT++ network simulations. SimProcTC aids in simulation parametrization, distribution, and visualization of results. Simulation distribution in SimProcTC is done through the Reliable Server Pooling (RSerPool) architecture, which was developed by the authors of SimProcTC, and is an accepted IETF standard. This architecture considers session failover and redundancy in intelligently distributing

simulations and managing a pool of servers running simulations.

Like SAFE, SimProcTC also contains a mechanism for visualization of experiment results. The framework uses R for both simulation parametrization and plotting of the results. Unlike SAFE though, the plotting functionality of SimProcTC is limited to static plots. These plots are defined during experiment configuration using a mechanism called *Plotting Templates*. These plotting templates are written in R, and thus for the experimenter to utilize SimProcTC's plotting mechanism, knowledge of R is required.

SimProcTC does allow for other plotting mechanisms other than its internal one to be used. This is accomplished by exporting the data into a space delimited table file that can be read into GNU Plot, GNU Octave, and Microsoft Excel. With this mechanism the user still must have some knowledge of plotting technologies, and exploratory data analysis may be difficult.

6.2 Akaroa2

In terms of scope, Akaroa2 [36] is very similar to SAFE, seeking to make network simulation research practical and user-friendly. It is constructed around the paradigm of Multiple Replications in Parallel (MRIP), also similar to SAFE. Akaroa2 is controlled through a Shell Command Interface, similar to that for SAFE's power users. It also has a graphical user interface named *akgui* which runs on the desktop platform.

In terms of visualization, Akaroa2 does not have the ability to interactively plot data. However, it does have a method for producing static plots through a series of scripts. These scripts query Akaroa2's Ingres relational database and produce plots and tables of coverage and speedup versus selected experimental conditions.

6.3 James II

Outside the area of network simulation, I have also found frameworks that closely align with the scope of SAFE. A notable example is JAMES II [19], which provides researchers in computational systems biology with support for modeling, experiment design and execution, run length control, experiment storage and retrieval, and data visualization and analysis. The concept of *plug ins*, which is widely applied in the architecture of JAMES II, imbues the framework with a great deal of adaptability. We have learned from this architecture and, in the development of SAFE, we are working toward defining clear interfaces between components which might be conceived of as plug ins.

James II also provides mechanisms for output analysis, both visual and statistical. James II's visual component for data analysis includes a line plot. This allows the experimenter to view any numeric metric as it evolves over time.

6.4 Chapter Summary

While many tools of similar scope to SAFE have the ability to generate static plots, few have the ability to generate rich, interactive visualizations. The fact that SAFE was designed to be accessible to novice users calls for interactive visualizations that are easy to manipulate. However, like other tools of similar scope, SAFE has an extendable tool for generating static plots. Unlike most tools, though, SAFE offers the its users interfaces that are appropriate to their levels of expertise.

Chapter 7

Conclusions and Future Work

The aim of data visualization goes far beyond the subjectivity of *beautiful* design. Information visualization reveals patterns and knowledge that would be nearly impossible to quickly discern with rote data analysis. The amount of data generated by network simulations make data visualization a powerful tool in analysis of results. My work of coupling a strong visualization tool with built-in techniques for reporting credible results provides a much needed contribution to the network simulation community.

This work fell under the umbrella of many disciplines including statistics, network simulation, graphic design, and cognitive psychology. SAFE's visualization tool was constructed after careful study of the research literature in these fields. The ultimate goal was to create a tool that lets the data speak for itself, effortlessly revealing its knowledge to all interested observers, from researchers to students. This work was a significant contribution to the advancement of SAFE, which ultimately benefits the ns-3 community.

One area of planned future work is to extend SAFE's static plotting component to cover a larger variety of graphics. Currently the static plotting tool only has the ability to create simple time series graphics. As more members of the network simulation

community start to use SAFE, a notion of what other graphic types may be useful will more easily obtainable. It is also planned to ensure that confidence intervals are added to the graphic if the data is available. Since the tool was developed with extendability in mind, adding these new graphic types will be straightforward.

Once a variety of graphic types are incorporated into the static plotting tool it can also be extended further for power users. A convenient method for doing this would be to include graphic configurations in the experiment configuration file. When the experiment finishes these plots could be placed in the user's compartment on the server. This allows power users to avoid the web user interface entirely.

Another area of future work is investigating techniques for dealing with data series either of different units or the same units with different magnitudes. Suggestions in the current literature mitigate the problem, but do not solve it completely. Both normalization and faceting can still distort relationships in the data depending on how data is normalized and the axes are scaled. Finding a better way to deal with this problem would improve the decipherability of the plots produced by SAFE's interactive visualization component.

A final area of planned future work is the expansion of the interactive plotting component. As shown in Section 4.5, I investigated numerous open source technologies which could have been leveraged by SAFE's visualization component. Unfortunately none of these tools turned out to be a good fit for integration with SAFE. One tool that was not mentioned and could be useful for developing graphics that are not time-series is Rickshaw [4]. Rickshaw's time-series capabilities do not align with SAFE's design criteria, but many of the other graphic types provided by Rickshaw could be useful in SAFE's interactive visualization component. Further work is warranted in investigation how these graphics could be integrated into SAFE's visualization tool.

My work with SAFE began as a general investigation into how it could progress from where Andrew Hallagan and Bryan Ward left off. It resulted in a coherent design for SAFE as well as an implementation of the visualization component of this design. Throughout this design and implementation process I uncovered issues that,

to my knowledge, are not discussed in network simulation literature. These problems include creating plots which do not scale attributes properly, misuse retinal variables, and use double axes, just to name a few. The potential problems which Pawlikowski et al. [37] discovered in network simulation publications only scratch the surface of a myriad of graphic mistakes. By automating the workflow of the data analysis process and providing a tool that encourages best practices I hope that publications in network simulation become more comprehendible, aesthetically pleasing, and most importantly credible.

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